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Invited review

Coastal lagoons and rising sea level: A review

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ABSTRACT

Sea-level rise (SLR) poses a particularly ominous threat to human habitations and infrastructure in the coastal zone because 10% of the world's population lives in low-lying coastal regions within 10 m elevation of present sea level. There has been much discussion about projected (and the sources of projection) vs. measured SLR rates. Which rates should coastal scientists and managers apply in their studies, and what is the degree of confidence of such forecasts, are still open questions.

This paper reviews the patterns and effects of relative SLR (RSLR) in coastal lagoons. Three main components are presented in the review: (a) a summary of the main approaches used in predicting medium- to long-term trends in RSLR, (b) a summary of the main evolutionary trends of coastal lagoons and the tools used to examine such trends, and (c) an identification of future research needs.

The review reveals that the major source of uncertainty is how and when RSLR will manifest itself at different spatio-temporal scales in coastal lagoon systems, and how its effects can be mitigated. Most of the studies reviewed herein articulate a natural 'defence' mechanism of barriers in coastal lagoons by landward barrier retreat through continuous migration, and a gradual change in basin hypsometry during the retreat process. So far, only a relatively small number of detailed studies have integrated and quantified human impacts and coastal lagoon evolution induced by RSLR. We conclude that much more research about adaptation measures is needed, taking into consideration not only the physical and ecological systems but also social, cultural, and economic impacts. Future challenges include a downscaling of SLR approaches from the global level to regional and local levels, with a detailed application of coastal evolution prediction to individual coastal lagoon systems.

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1. Introduction

Sea-level rise (SLR) is amongst the most important yet complex and often misunderstood aspects of climate change. Not surprisingly, there have been many recent reviews of SLR, including those of Cazenava and Llovel (2009), Willis et al. (2010), Church and White (2011), Gehrels et al. (2011), Nicholls et al. (2011), and Pfeffer (2011). The question of how much and when SLR will occur in the future has been prominent since the earliest US Environmental Protection Agency and initial Intergovernmental Panel on Climate Change (IPCC) estimates of climate change and its consequences (IPCC, 2001).

Climate projections like those of the IPCC (2001, 2007, 2014) are increasingly used in decision-making, and the most recent projections from the 5th Assessment Report (AR5) consider a scenario of very high emissions, and predict a global rise of 52–98 cm by the end of this century, which would threaten the viability of many coastal cities (Fig. 1). There has been little criticism of the AR5 projections (IPCC, 2013, 2014), but shortcomings have been identified in the previous 4th assessment report published in 2007 (AR4). The work of Rahmstorf and Cazenave (2012) took a very interesting approach in testing the AR4 projections, and discovered that the central SLR predictions were too low by about 60% (as the IPCC models did not include the effects of dynamic ice processes). Moreover, Vermeer and Rahmstorf (2009) used a semi-empirical method linking temperature changes to SLR, and the resulting projected global sea level rise by 2100 of 75–190 cm is significantly higher than the IPCC AR4 projections. Several other recent studies have also projected that global mean sea level rise by 2100 will be close to 1 m (Rahmstorf and Cazenave, 2012).

However, what matters most to the coastal morphological equilibrium is not the global-mean projected SLR rate itself, but the local change in the observed relative sea-level rise (RSLR). Possible causes of regional sea-level variations include gravitational effects resulting from land ice mass changes, thermal expansion, and ocean dynamics (Slangen et al., 2012). RSLR has already been identified in the literature (e.g., Church and White, 2006; Kirwan and Murray, 2008; Kirwan et al., 2008; Chust et al., 2009; Gillanders et al., 2011) as a critical variable for the establishment and maintenance of biotic coastal communities, as a threat to biodiversity, and as being responsible for the increasing magnitude and spatial extent of storm surge flood hazard (e.g., Bilskie et al., 2014), amongst other issues. Indeed, the impacts of RSLR are already evident in several different coastal regions (e.g., IPCC, 2007). However, regarding morphological feedback, there is still a lack of critical examination of the dimensions of the physical changes that will occur in coastal areas worldwide (Orford and Pethick, 2006; Nicholls et al., 2007). Perhaps the most serious and widely recognized issue facing coastal conservation is the impact of RSLR on coastal landforms in coastal lagoons and estuaries. Coastal lagoons are here considered as "*inland water bodies separated from the ocean by a barrier, connected to the ocean by one or more restricted inlets which remain open at least intermittently, and have water depths which seldom exceed a few metres*" (Adlam, 2014). About 32,000 lagoons are reported along 13% of the world's coastline (Carter and Woodroffe, 1994), with a coastline contribution estimated at 17.6% for North America, 12.2% for South America, 5.3% for Europe, 17.9% for Africa, 13.8% for Asia, and 11.4% for Australia (Barnes, 1980).

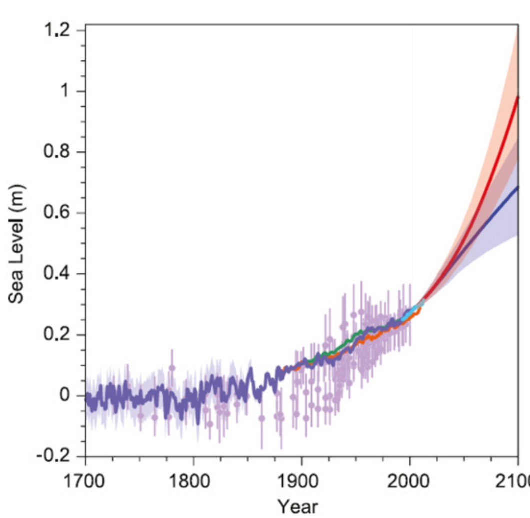

Fig. 1. Past and future sea-level rise. For the past, proxy data are shown in light purple and tide gauge data in blue. For the future, the IPCC projections for very high emissions (red, RCP8.5 scenario) and very low emissions (blue, RCP2.6 scenario) are shown (source: IPCC, 2014, AR5 — Fig. 13.27). Sea-level values on the y-axis are shifted by the mean sea level between 1700 and 1850 (about 20 cm below mean sea level).

The size of coastal lagoons varies substantially, with surface areas ranging between 10,200 km^2, as in the case of Lagoa dos Patos in Brazil (Pilkey et al., 2009) to a few tens of square kilometres, as the case of Ria Formosa lagoon in Portugal at 84 km^2 (Carrasco et al., 2008). Coastal lagoons are relatively young features, have formed over the last 5000–7000 years, and are often short lived over geological timescales because of sedimentation (Martin and Dominguez, 1994). Most coastal lagoons are maintained only by the protection afforded by barriers and spits, presenting very peculiar feedbacks to RSLR (List et al., 1997), and some of them have been highly modified and constrained because of human settlements (e.g., Chesapeake Bay in Gibbons and Nicholls, 2006; the Gold Coast in Cooper and Lemckert, 2012). Although the responses to the effects of RSLR observed in coastal lagoons are manifest in different contexts (e.g., physical, ecological, and economic) and over different time scales, only the physical changes (inundation and sediment supply) are discussed in the present work.

Geological observations reveal that many barrier systems worldwide have been able to keep pace with RSLR for thousands of years (McBride et al., 2013). These systems can have spatially distinct responses to RSLR, as in the case of the Gulf of Mexico, which is composed of several bay/lagoon stretches and barriers, where previous studies (e.g., Troiani et al., 2011) have reported rapid and dramatic morphological changes resulting from RSLR but also spatial differences in the response. Other case studies showing the influence of RSLR on lagoons and/or estuaries include Lagoa dos Patos, Brazil (e.g., Toldo et al., 2000), Lake Illawarra and St. Georges Basin, New South Wales, Australia (e.g., Sloss et al., 2006), Venice Lagoon, Italy (e.g., Ferla et al., 2007), Pamlico–Albemarle Sound, North Carolina, United States (e.g., Pilkey et al., 2009), Wadden Sea, Netherlands/Germany (e.g., Dissanayake et al., 2012), Ria Formosa, Portugal (e.g., Andrade et al., 2004), Vistula Lagoon, Baltic Sea (e.g., Navrotskaya and Chubarenko, 2013), and Manzala Lagoon, Egypt (Frihy and El-Sayed, 2013).

In addition to the direct link between RSLR and physical systems, morphological changes resulting from RSLR can also lead to drastic consequences in the social–economic frame (Nicholls and Tol, 2006). Anthoff et al. (2006), in a study dedicated to all types of coast, estimate that 145 million people live within 1 m of present-day mean sea level, and regionally, the most threatened lands are North America, central Asia, and unpopulated Arctic coastlines (Anthoff et al., 2006). According to Nicholls et al. (2006), the average annual costs for protecting coastlines are assumed to be a linear function of the rate of RSLR and of the proportion of the coast that is protected. The costs increase by an order of magnitude if the rate of RSLR is higher than 1 cm year^{-1} (i.e., protection costs are much higher for the 1 m and 2 m rise scenarios than for the 0.5 m scenarios).

Understanding how RSLR is likely to affect coastal regions (in particular lagoons) and consequently how society will choose to address this issue in the short term in ways that are sustainable for the long term is a major challenge for both scientists and coastal policy-makers and managers (CCSP, 2009). The need for adaptation to climate change is evident, and much more research concerning the physical impacts from RSLR is still required, particularly because most of the adaptation measures will involve large and ongoing costs (Nicholls and Tol, 2006; Woodroffe and Murray-Wallace, 2012). The present work reviews the previous research on coastal lagoon evolution associated with RSLR and the main modelling results for coastal lagoon systems. Emphasis is placed on the physical constraints (morphological changes in intertidal areas) rather than on the biological/ecological processes or social–economic–cultural consequences. Three foci to the review are presented: (a) summarizing the main approaches used in predicting medium- to long-term trends in SLR; (b) identifying the main evolutionary trends of coastal lagoons and the tools used to examine such trends; and (c) highlighting the aspects that require further research.

2. Morphological effects of RSLR in coastal lagoons

It is often difficult to make predictions of coastal change at larger scales in coastal lagoons, due the non-linearity of coastal sedimentary processes. In particular, the temporal 'upscaling' of processes from smaller scales to those relevant to coastal management (or vice versa) is a difficult (and sometimes ill-advised) practice, and limits our capacity to predict future coastal change (Ashton et al., 2007). Coastal lagoons enclose morphologies presenting different spatial scales, ranging from bed forms (~cm to m) such as ripples and dunes, to channel–shoal patterns, vegetated salt marshes, and full basins (~1–100 km, Carter and Woodroffe, 1994; Hibma et al., 2004), which have complex evolutions that do not follow a specific formula or respond in a linear fashion to forcing factors. The whole basin system (mega-scale), includes barriers, inlets, basins, and marshes, and embraces different morphological elements (macro-scale) and various morphological features inside each element (meso-scale) responding differently, both temporally and spatially, to physical changes (Ranasinghe et al., 2012). Barriers and channels are constrained by boundary conditions, and the cycle of evolution taking place is bound by the principle of Markovian inheritance, whereby the product of previous changes (i.e., antecedent topography and hydrology) provides the initial conditions upon which future evolutionary processes build (Cowell and Thom, 1994).

The geological evolution of a lagoon is typically expressed in terms of the rate of basin fill through sedimentation. It is thus helpful to consider the lagoon fill in terms of maturity (Roy et al., 2001; Smith, 2001). Immature lagoons are newly inundated shallow depositional basins, with few geomorphic units and no predominance of coastal vegetation (e.g., *Spartina* sp.), and in which the entire volume of the water body is available to accommodate sediment (i.e., the volume of empty space behind the barrier that would need to be filled with sediment in order to reach sea level, hereafter referred to as accommodation space; Roy et al., 2001). In contrast, mature lagoons are entirely filled with sediment, accommodation space has been exhausted, and river discharge flows directly to the coast (Adlam, 2014). Those lagoons present an expansive area, with little sand deposition and a predominance of aquatic vegetation, and are directly dependent on sediment changes occurring in the fronting barriers. Most processes operating within lagoons affect the degree of maturity through the creation and consumption of accommodation space. The rate of consumption of accommodation space is dependent on the rate and availability of sediment supply (Roy et al., 2001; Boyd et al., 1992).

2.1. RSLR and the evolution of barriers and inlets

As sea level rises, barrier islands tend to migrate inland (e.g., Swift, 1975; Zhang et al., 2004; Masetti et al., 2008; Moore et al., 2010). Besides RSLR, other factors that control rates of island migration include the underlying geology (e.g., Riggs et al., 1995), the stratigraphy (e.g., Storms et al., 2002; Moore et al., 2010), sediment grain size (e.g., Storms et al., 2002; Masetti et al., 2008), substrate slope (Storms et al., 2002; Wolinsky and Murray, 2009; Moore et al., 2010), and substrate erodibility (Moore et al., 2010).

Although our overall understanding of how barrier islands respond to climate change continues to improve, little is known about how the connectivity of the two constituent landscape systems (i.e., barriers and inlets) affects the evolution of coupled barrier–marsh systems under changing conditions (Walters et al., 2014). Under rising sea level, barriers will lose areal extent at a rate equal to that at which the barrier island rolls over the marsh platform, unless the marsh progrades into the bay or up the mainland slope as it is flooded by the rising sea level (Moore et al., 2014). Recent findings from Watson (2011) and Walters et al. (2014) suggest that barriers backed by marshes have the added benefit of reduced accommodation space, which allows an island to remain "perched" on the marsh, compared to islands backed by open bays, which must migrate further landwards to maintain elevation relative to sea level. In fact, marsh-backed islands, compared with bay-backed islands, appear to be less vulnerable to rising sea level because they are able to maintain a more offshore position without a significant contribution of sand from alongshore transport or from the shoreface (Walters et al., 2014).

An increase in the rate of RSLR will gradually change the hypsometry of the backbarrier, transforming supratidal areas to open-water and intertidal environments, as observed by Ashton et al. (2007). RSLR will cause changes in inlet geometry or in tidal forcing, affecting the baseline level of transport through the inlet(s), and thus to the interior (Smith, 2001). Fig. 2 illustrates the equilibrium volumes of the elements of an inlet as a function of SLR for the Dutch Wadden Sea (van Goor et al., 2003): with a higher rate of RSLR, the dynamic equilibrium volume of the channel increases and the dynamic equilibrium volume of the ebb-tidal delta decreases. Those authors assumed the existence of a dynamic equilibrium to predict critical rates of SLR for inlet–basin systems. In Fig. 2, as the sediment demand for a smaller basin decreases, the inlet adapts more easily to a higher rate of SLR, for the same hydrodynamic and sedimentological conditions. For the basins considered, a gradual deepening over time of the tidal basin prompted an importation of sediment (van Goor et al., 2003).

Even if detailed descriptions exist of the responses of barrier chains and inlets to RSLR, as well as various attempts to systematize the foreseen impacts, there remains a deficiency in the conceptualization of expected morphological changes and their importance at the regional/local scale that is presented in a straight-forward manner and which can be rapidly assessed by decision-makers. Penland et al. (1988) were amongst the first to conceptualize the long-term scenario response of a low-lying system to RSLR, referring to the system as a delta-type coast (namely, the Mississippi Delta). Although lacking some details about the prediction of the readjustments to inlet geometry, those authors proposed an interesting morphological scheme showing the reworking of sand deposits in an abandoned headland into flanking barriers, as well as the creation of a lagoon behind a barrier island (Penland et al., 1988). Focussing more on coastal lagoons, Fitzgerald et al. (2006) developed a conceptual scheme (Fig. 3) that describes the barrier–inlet–basin cell feedback in relation to RSLR, and which can be used to interpret long-term changes in coastal barrier systems. Fitzgerald et al.'s (2006) scheme is more comprehensive than that of Penland et al. (1988), and has wider application. It addresses the fate of mixed-energy barrier coasts found throughout the northeastern coast of the United States, the East Friesian Islands in the North Sea, and the Copper River delta barriers in the Gulf of Alaska, which are characterized by short, fragmented, stubby barrier islands, numerous tidal inlets, well-developed ebb-tidal deltas, and a backbarrier consisting of salt marshes and tidal flats incised by tidal creeks. In essence, the model of Fitzgerald et al. (2006) represents the conversion of marsh to open water, causing an increase in the tidal prism and growth of the ebb shoals (a stable barrier to transgression, Fig. 3; Gaudiano and Kana, 2001). The general progression through the different stages in this model is robust; however, the rate at which the coast evolves given a certain rate of sea-level rise, and the thresholds involved, are unknown (van Goor et al., 2003). For example, it has not been determined at what stage an inlet will be transformed from a channel system that naturally flushes sand by dominant ebb tidal currents to one in which dominant flood tidal

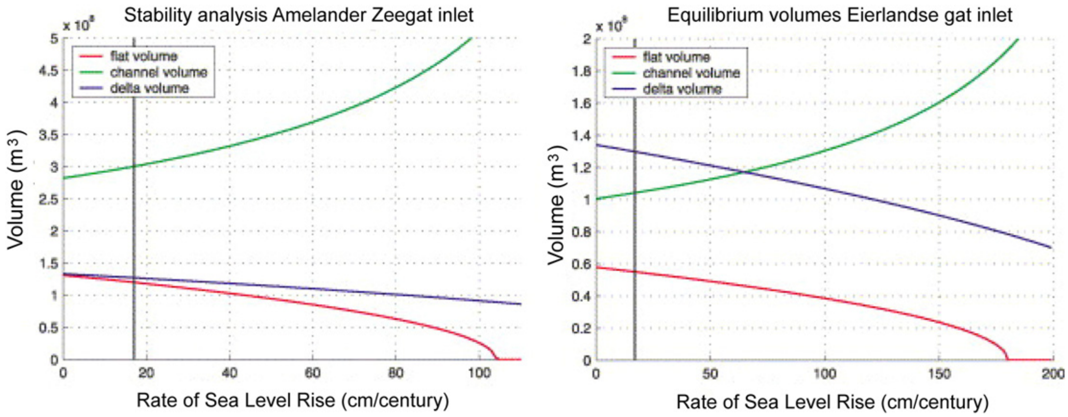

Fig. 2. Dynamic equilibrium volumes of tidal inlet elements (see text in Section 2.1) as a function of SLR rate for Amelander Zeegat and Eierlandse Gat. The vertical line in each case represents the assumed state of dynamic equilibrium under the considered rate of SLR (source: van Goor et al., 2003).

currents import sand to the backbarrier (Ashton et al., 2007). The model is also restricted in application, as it predicts only marine sediment input to the lagoon, and no other additional sediment input sources to the lagoon are considered. Many other investigations have also demonstrated that the relative strength of the ebb versus the flood tidal flow, which controls the net movement of bed load through an inlet, is a function of inlet geometry, bay tidal prism, and backbarrier hypsometry (e.g., Boon and Byrne, 1981).

Prior to the study of Fitzgerald et al. (2006), Fitzgerald et al. (1984) had already illustrated, with respect to the evolution of the Friesian Islands, what can happen to a barrier chain when an alteration of backbarrier hypsometry induces changes in the tidal prism, although the earlier study did not incorporate a relevant conceptual schematisation. During a 310 year period, the backbarrier area of the Friesian Islands decreased by 30% due mostly to land reclamation of tidal flat areas along the landward sides of the barriers and along the mainland shore. Secondary losses were attributed to re-curved spit extension into the backbarrier. These processes resulted in a reduction in the tidal prism and a coincident narrowing of the tidal inlets by 52% (Fitzgerald et al., 1984).

Most of the findings of Fitzgerald et al. (2006) were subsequently corroborated by the case study of Dissanayake et al. (2012). The investigations of Ganju and Schoellhamer (2010) and Dissanayake et al. (2012) were the first to address the morphodynamic impact of RSLR on inlet systems using a numerical model.

2.2. RSLR, sediment supply, and basin evolution

Depending on local basin geometry, sediment availability, freshwater delivery, and tidal velocity, RSLR causes sediment import or export (see Friedrichs et al., 1990). In the case of a flood-dominated tidal lagoon, RSLR tends to result in sediment accumulation as a means of restoring the intrinsic dynamic equilibrium of the basin (Dronkers, 1998). Thus, besides the direct barrier and inlet adjustments, RSLR also affects the basin drainage area. Redfield (1965) were the first to provide evidence of concomitant bay infilling and lateral progradation of the intertidal marsh onto sand flats, where existing meandering channels were stabilized by the marsh itself through narrowing of the channels until the flow was concentrated enough to prevent further erosion or deposition.

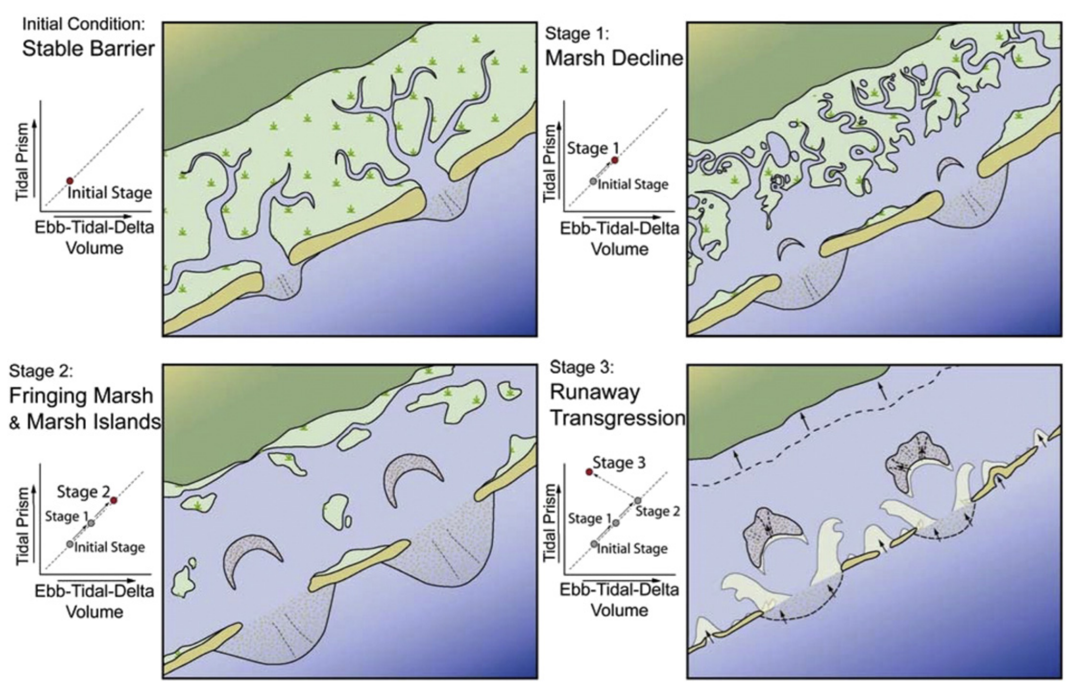

Fig. 3. Conceptual model of mixed-energy barrier coast evolution in a regime of accelerating SLR (source: FitzGerald et al., 2006).

A relevant conceptualization of tidal basin response to accelerated RSLR, using the Wadden Sea as an example, is expressed at Fig. 4. The graph in that figure is consistent with the conceptual model proposed by Fitzgerald et al. (2006), and highlights the concept of 'adjustment' inside the tidal basin. The scheme proposed by Fitzgerald et al. (2006) is focused mostly on the SLR–inlet–backbarrier relationship, whereas the Louters and Gerritsen (1994) scheme details the steps of adjustment inside the lagoon, namely, regarding the depth of the basin, after an increase in the rate of RSLR. The Louters and Gerritsen (1994) model also assumes that there is a dynamic balance between sediment supply, ecosystems, and changes in sea level; indeed, as stated by the Bruun rule (Bruun, 1962), an equilibrium state is assumed in the periods between adjustments to RSLR. Therefore, the system's response to the rise is delayed and the average basin level thereby becomes slightly lower in relation to sea level. If the sea level rises at an increased rate, the tidal basin deepens slightly over time in relation to the rising sea level. At the beginning of this process, the sand retention capacity of the deepened basin gradually increases (Fig. 4). The total quantity of sand required to restore dynamic equilibrium is directly proportional to the rate of RSLR. If the supply of sediment is not sufficient to allow the tidal area to keep pace with RSLR, dynamic equilibrium cannot be regained. In that case, the level of the lagoon will gradually lag behind the rise in sea level, eventually bringing about the area's inundation (Louters and Gerritsen, 1994). The findings of Louters and Gerritsen (1994) have been subsequently discussed in the study of Gerritsen and Berentsen (1998), who modelled sediment balance in the wider North Sea Basin for the Holocene SLR, but for a single tidal basin scale. Nevertheless, and compared with other recent studies, results from the application of the Louters and Gerritsen (1994) model to the Wadden Sea are ambiguous, as they predict a long-term net import of sediment budget of the Dutch coastal system, whereas other studies, such as Bonekamp et al. (2002), suggest sediment export due to substantial tidal asymmetries.

Other recent and relevant studies of basin evolution include the work of Defina et al. (2007), who developed a conceptual model for Venice Lagoon, showing the same patterns of evolution described in Louters and Gerritsen (1994). Other studies also include the work of Lopes et al. (2011), who applied the morphodynamic model MORSYS2D to Ria de Aveiro, and described impacts of RSLR on lagoon hydrodynamics that included an increase in the tidal prism at the lagoon mouth of about 28%, as well as an intensification in sediment fluxes, and, consequently, bathymetric changes. More recently, Dissanayake et al. (2012) modelled a typical large inlet/basin system, the Ameland Inlet, over a 110 year study period, and found an existing flood dominance of the system with increasing rates of RSLR, caused by erosion of the ebb-tidal delta and accretion of the basin. van der Wegen (2013) showed that the intertidal area might disappear under realistic RSLR rates, with the basin shifting from a sediment-exporting system to an importing system, as well as the basin 'drowning' and a considerable reduction in the extent of intertidal areas.

The recent review by Coco et al. (2013) of the morphodynamics of tidal networks discusses tidal drainage accommodation space and how tidal channels increase in both width and depth as a result of RSLR and related changes in the flowing tidal prism. Stefanon et al. (2012) provided similar findings, reporting a linear relationship between the tidal prism and the drainage area of the basin, and showing that a decrease in the tidal prism leads to smaller channel cross-sections and a general retreat of the channels, whereas the opposite effect (network expansion and larger cross-sectional channel areas) occurs when the tidal prism increases.

2.3. RSLR and salt marsh evolution

A good way of predicting the maturity of coastal lagoons is to evaluate mineral deposition rates within salt marshes if they keep up with RSLR (e.g., Edwards, 2007; Cronin, 2012). Marshes cover extensive areas of estuarine and deltaic environments in mid- to high latitudes and support different vegetation types, and also show different rates of inundation and suspended sediment delivery (e.g., Fitzgerald et al., 2006; French, 2006; Cronin, 2012). Besides the influence of RSLR, salt marsh maintenance is also influenced by factors such as sediment supply and tidal range (Reed, 1995). Rising water levels could potentially alter the inundation regime in salt marsh habitats, leading to irreversible states. Rizzetto and Tosi (2012) found that both RSLR and the frequency of high tides at Venice Lagoon greatly influenced shifts in the margins of the salt marsh and the meander evolution of tidal channels in the long term, but short-term changes in creek sinuosity were often also closely related to variations in tidal range. The retreat of marsh margins, the increase in network density, and the decrease in creek sinuosity provided evidence for tidal channel development in a regime of RSLR (Rizzetto and Tosi, 2012).

The physical responses of salt marshes to RSLR have been frequently coupled with morphological models (e.g., Schwimmer and Pizzuto, 2000; Mariotti and Fagherazzi, 2010; Coco et al., 2013). Recent studies have aimed to improve understanding of the morphological development of marshes by considering factors such as the rate of RSLR, the

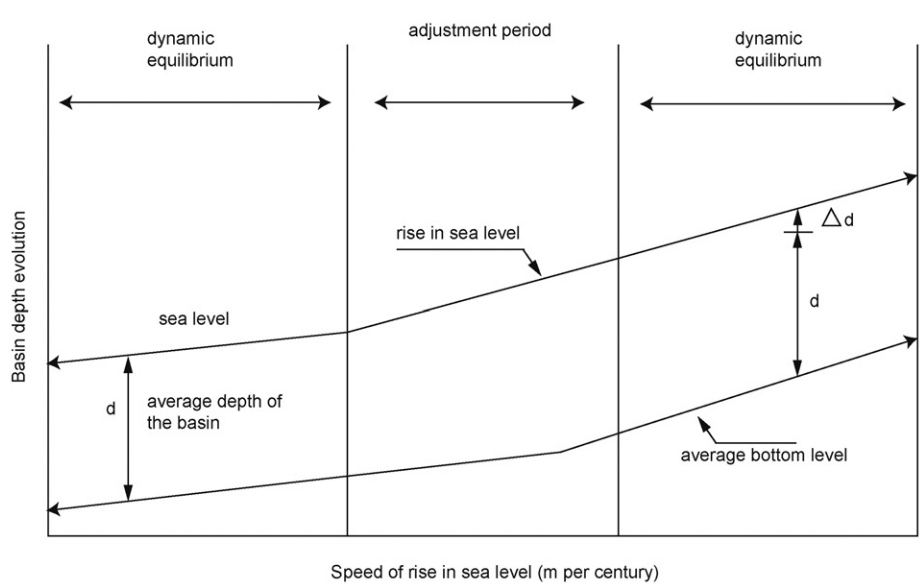

Fig. 4. Adaptive behaviour of tidal basins with changes varying over time (adapted from Louters and Gerritsen, 1994).

depth of inundation, inorganic sediment supply, plant productivity, and the accumulation of organic material (e.g., Fagherazzi and Sun, 2004; D'Alpaos et al., 2005; Kirwan et al., 2008). In these models, morphological changes are based on the balance between erosion (dependent on shear stress criteria), inorganic accretion, and organic production, as found from empirical relationships (Morris et al., 2002). Furthermore, successive versions of the Sea Level Affecting Marshes Model (SLAMM) have been used to estimate the impacts of SLR along the coasts of the United States (e.g., Titus et al., 1991; Craft et al., 2009; Traill et al., 2011; Glick et al., 2013). Many other modelling approaches have been developed, about which additional information can be found in Kirwan and Temmerman (2009) and references therein.

Besides numerical modelling, other approaches have been used to determine the response of salt marshes to RSLR. For example, using a lab flume experiment, Stefanon et al. (2012) explored the morphological impact of sea-level fluctuations (both decrease and rise) on a tidal network pattern, and demonstrated rapid network adaptation as a result of varying mean water levels and associated tidal prisms. Simulations of these interactions show that salt marshes are able to keep up with RSLR up to a certain threshold rate (e.g., Kirwan et al., 2010).

In fact, the published model results show that salt marshes are constantly adjusting towards a new equilibrium (Morris et al., 2002); therefore, the interplay between sediment dynamics and the rate of RSLR has been suggested as being critical for the establishment of the equilibrium intertidal area configuration (Marani et al., 2007). This has also led to the idea that salt marshes attain equilibrium but rather continuously lag and attempt to readjust to changes in sea level (Kirwan and Murray, 2008). Nevertheless, the recent work of Swanson et al. (2015) for San Franscico Bay report salt marsh adaptation and survival for high rates of SLR (with SLR ranging from 43 to 179 cm), in agreement with Schile et al. (2014). Notwithstanding this, the Swanson et al. (2015) model still lacks calibration and validation.

The ability of marshes to rapidly accrete vertically and horizontally under favourable conditions reinforces the notion that natural marshes can quickly respond to external forcing (Friedrichs and Perry, 2001; van Wijnen and Bakker, 2001). Marshes will be under severe stress only if the supply of sediment and the build-up of organic material cannot keep up with rising sea level (e.g., Morris et al., 2002; Nielsen and Nielsen, 2002; Temmerman et al., 2004; French, 2006; Kirwan and Temmerman, 2009; Andersen et al., 2011). For instance, the recent expansion of water-logged panes in salt marshes in the northeastern United States has been attributed to tidal flooding associated with accelerated rates of RSLR (Hartig et al., 2002). Sediment supply reduction and increased subsidence rates were partially responsible for the reductions in the extent of marshland in Chesapeake Bay and Venice lagoon marshes (Reed, 1995; Day et al., 1998; Marani et al., 2007).

Salt marsh growth and development substantially alters the sedimentary processes occurring in lagoons (Fagherazzi et al., 2012; Coco et al., 2013). Herein, we propose a generic conceptual scheme illustrating salt marsh development with respect to RSLR (Fig. 5). It is assumed that the salt marsh accretion rate is the net product of sediment deposition and physical compaction (Bartholdy et al., 2004), as well as being dependent on the ground biomass (McKee et al., 2007). Essentially, RSLR is portrayed as creating accommodation space in which fine-grained sediments can settle (sediment supply rate), so that increases in the rate of RSLR theoretically lead to concomitant changes in the rates of mineral sediment deposition (in agreement with the results of Redfield, 1972); however, under high rates of RSLR, with an insufficient supply of sediment and organic material, inundation of the salt marsh will occur. In contrast, if the rate of sediment supply is much higher than the rate of RSLR, silting-up dominates and the marsh will shift towards a different environment and ecosystem (an infilling lagoon).

Assuming a sufficient supply of sediment, and after an initial phase of growth, the SMG (salt marsh growth) rate will tend to attain equilibrium with the rate of RSLR (Fig. 5, central panel), and the salt marsh surface, also referred to as the marsh platform, will be at a level just below

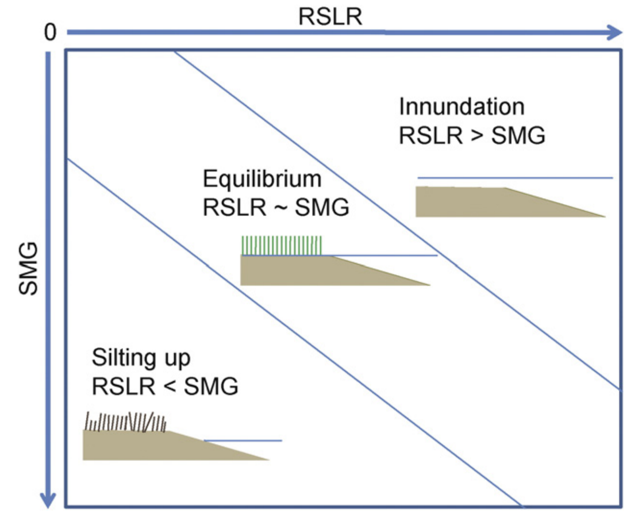

Fig. 5. Conceptual scheme showing salt marsh response to relative sea level rise (RSLR) and salt marsh growth (SMG).

the highest (astronomical) tide, depending on local tidal conditions and tidal range (Allen, 2000). The elevation of the platform relative to sea level determines the total wetland area, inundation frequency and duration, and wetland productivity (Morris et al., 2002). If SMG rates are too low to keep pace with the rate of RSLR (slow growth as result of low silt input), the intertidal area in the lagoon is dominated by inundation, and there is no effective salt marsh development (Fig. 5, upper panel). If the amount of inundation becomes sufficient to stress or kill vegetation, then the marsh substrate begins to break up as peat collapses. Under these conditions, salt marshes cannot adapt and may drown, and even the lower part of the substrate may become eroded (Kirwan et al., 2010; Cronin, 2012), and inner channel networks will expand (Hartig et al., 2002). There is no predefined time lag applying to when the marsh substrate begins to break up (or recover), and future research must seek to estimate the resilience capacity (and associated time spans) of these areas. This threshold appears to have already been reached for many of coastal Louisiana's wetlands, owing to a number of anthropogenic and natural factors (Morton et al., 2005). In contrast, if SMG rates are higher than rates of RSLR (rapid growth as result of excessive silt input), the intertidal area becomes sediment saturated and the salt marsh will shift horizontally if there is enough accommodation space (Fig. 5, lower panel). The process leads to a loss of inner-basin area and a continuation of infilling, potentially causing detrimental effects in the salt marsh over the long-term.

Determining the clear effects of each of them remains difficult, because the effects of RSLR alone cannot be isolated in natural wetlands. Even if we presume that vertical accretion in salt marshes is solely a function of inorganic and organic matter influx and ignore the effects of regional subsidence along coastlines, it is clear that many marshes will not be able to keep up with the projected increase in the rate of SLR after some time, which might result in the partial conversion of marshlands to subtidal and unvegetated intertidal areas (Ashton et al., 2007). The ultimate submergence of coastal marshes occurs when there is insufficient elevation to prevent excessive water logging of the marsh soil, as observed by Reed (2002) in the Mississippi salt marshes.

Day et al. (1998) compiled information about salt marsh accretion rates, reporting a vertical accretion rate of 0.3–2.3 cm year^{-1} in Venice lagoon as measured over two years. Fitzgerald et al. (2006) reported an interval of 0–14 mm year^{-1}, with a mean rate of 5.0 mm year^{-1}. Pethick (1992) measured accretion rates of >2.0 cm over two years in a salt marsh in England, although this was not specifically for a coastal lagoon. In a large number of coastal systems worldwide, the accretion will be insufficient to prevent water-logging of marsh soil, leading to plant deterioration. This could be particularly relevant by the end of the twenty-first century, because the overall 74 cm of SLR (projected by the IPCC RCP8.5 scenario) includes an acceleration in SLR from the present day until the end of the century. The exceptions would be places with high availability of sediment, where salt marshes can survive under a rate of RSLR in excess of 1 cm year^{-1} (as observed in the Mississippi Delta by Reed, 2002).

The adjustment of salt marshes to RSLR also depends on the acceleration of sea-level rise. The experimental results of Kirwan and Temmerman (2009), as illustrated in Fig. 6, help to quantify the strength of the lagoon inundation–accretion feedback and the response of marsh accretion rates to step-by-step changes in the rate of RSLR. The results of Kirwan and Temmerman (2009) suggest that regardless of the magnitude of change, a marsh adjusts to a change in the rate of RSLR within about 100 years (returns to equilibrium, Fig. 6). Sediment availability is assumed, and the forecast accretion occurs because a feedback is considered between inundation and suspended sediment concentrations (sediment deposition rates are proportional to inundation depth) that allow marshes to quickly adjust their elevation to a change in the rate of sea-level rise. The long-term behaviour as suggested by the experiments of Kirwan and Temmerman (2009) fits some of the behaviours observed in the Louisiana wetlands (DeLaune et al., 1994), but does not match other response scenarios such as the expansion of drainage networks of tidal creeks in Cape Romain, South Carolina (Hughes et al., 2009), because the marsh feedback mechanisms of mineral deposition are very complex and are attributed mainly to changes in sea level.

Abiotic parameters also control salt marsh responses. Riverine-dominated salt marshes (such as many Gulf Coast and Chesapeake Bay marshes) experience greater sediment accumulation as a result of enhanced input of inorganic sediment compared with marshes, where the major source of inorganic sediment is marine (Fitzgerald et al., 2006). Lagoon marshes that do not experience significant fluvial delivery of inorganic sediment may therefore be at greater risk of inundation with rising sea level, as the main source of inorganic sediment to these marshes is the ocean, via tidal inlets. In coastal lagoons and estuaries, an absolute increase in the elevation of the marsh platform in response to rising sea level should cause a landward migration of the marsh (Gardner and Porter, 2001), and this may change the areal extent of wetland and consequently total production, depending on local geomorphology and anthropogenic barriers to migration. Further details can be found in the very recent study of Passeri et al. (2015), which examines the dynamic effects of SLR on low-gradient coastal landscapes.

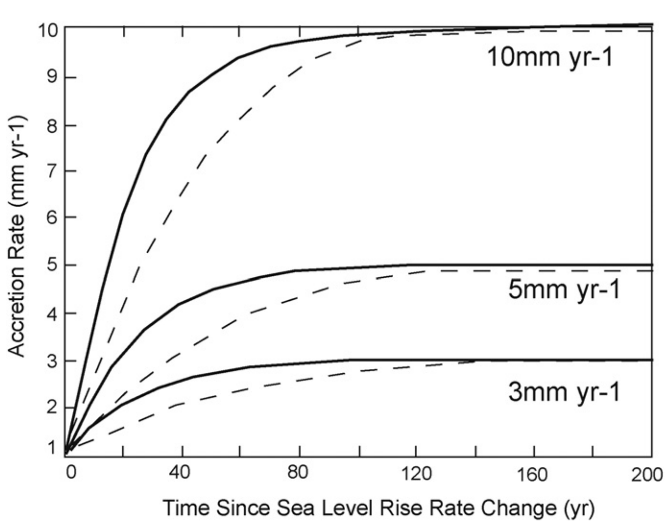

Fig. 6. The response of modelled accretion rates to step changes in the rate of RSLR. Experiments begin with a marsh surface in equilibrium with a 1 mm year^{-1} rate of RSLR. RSLR rates increase abruptly to 3, 5, or 10 mm year^{-1} at time zero. Black line: Morris model (Morris et al., 2002); dashed line: Temmerman model (adapted from Kirwan and Temmerman, 2009).

3. Modelling the evolution of coastal lagoons under RSLR scenarios

Numerical models have proved to be fundamental tools for gaining insights into barrier evolution and resilience, and have evolved significantly in the last 20 years. They have been developed and validated mostly for ocean front beaches and have only rarely been applied to the overall evolution of coastal lagoons. Indeed, there is a lack of model predictors adapted to the study of coastal embayments and lagoons. The following review is therefore focused on morphodynamic models that are commonly used in coastal applications, but which have apparent applicability to coastal lagoons.

Models relating SLR and coastal evolution have been developed for making long-term predictions, and in the last 20 years have experienced huge improvements in complexity, applicability, and reliability (Roelvink, 2006). Such models can be split into three main groups: simple shoreline models, behaviour models, and process-based models. These models can be applied at various degrees of dimension. One-dimensional models are ideal for studying, for example, width-average equilibrium profiles; two-dimensional models account for the formation of depth-averaged features (e.g., a channel or shoal); and three-dimensional models additionally account for small-scale hydrodynamic changes in the vertical dimension, that is, due to curvature or density gradients (Hibma et al., 2004; Lesser et al., 2004).

The older and most widely used sandy shoreline response models include the Bruun rule (Bruun, 1962) and modifications to the Bruun rule (e.g., Dubois, 1992; Davidson-Arnott, 2005). Several studies claim to have demonstrated the applicability of the Bruun rule (e.g., Leatherman et al., 2000; Zhang et al., 2004), and, perhaps because of its elegant simplicity, its use has become commonplace by coastal planners and managers (Pilkey and Cooper, 2004). In the last 10 years, criticisms of the Bruun rule have been many and varied (e.g., Sallenger, 2000; Cooper and Pilkey, 2004). Several authors have pointed out that this principle is applicable only to a restricted number of beaches (coasts without net alongshore sediment transport; Brunel and Sabatier, 2009). Consequently, several modifications to the Bruun rule have been made in attempts to attain greater accuracy in representing the response of the beach profile to SLR (e.g., Komar et al., 1991; Fitzgerald et al., 2008; Rosati et al., 2013).

During the 1990s, a suite of quantitative morphological behaviour models was developed, namely, the large-scale coastal behaviour (LSCB) models. Behaviour models are used to simulate the large-scale morphological and stratigraphic evolution of coasts that occurs as a result of changes in sea level and in sediment supply (e.g., Cowell et al., 1995; Niedoroda et al., 1995; Stive and de Vriend, 1995). Similar to the way in which shoreline response models use time as a surrogate for processes, the LSCB models utilize geometric cross-shore profile parameters as proxies for processes. As an example, the Integrated Assessment Models (IAMs) appeared at the beginning of the twenty-first century and are used to evaluate the vulnerability of coastal systems to multiple climate change impacts. The ability to achieve a fully integrated assessment of coastal vulnerability, considering dynamic interactions between sectors and/or processes, makes IAMs very useful in supporting policy- and decision-making at various scales. However, given the complex nature of such models, their implementation requires significant expertise. FUND, DIVA (Dynamic Interactive Assessment Model), SimCLIM, and RegIS (Regional Impact Simulator) are examples of IAMs dealing with the valuation and management (in terms of adaptation) of multiple climate change impacts on coastal areas and related ecosystems (see Hinkel, 2005; Holman et al., 2008; Warrick, 2009; Mcleod et al., 2010). For example, FUND is an integrated assessment model with a coastal impact component that includes country-level cost functions for dry land loss, wetland loss, forced migration, and dike construction (Tol, 2007); it works at the sector level, so that economic costs can be estimated for SLR. DIVA is a dedicated coastal impact model employing subnational coastal data (Vafeidis et al., 2008), and considers additional impacts such as coastal flooding and erosion as well as adaptation in terms of protection via dikes and nourishment (Hinkel and Klein, 2009). DIVA assesses coastal flood risk based on the hydrological elevation and extreme water level distributions (Hinkel et al., 2013) and erosion based on a combination of the Bruun rule and a simplified version of the ASMITA (Aggregated Scale Morphological Interaction between Tidal inlet and Adjacent coast) model for tidal basins (Nicholls et al., 2011). Further details can be found in the scientific review of Mcleod et al. (2010).

In clear contrast to the aforementioned behaviour models are the 2D process-based models and the recent 3D circulation process-based models, which when coupled with sediment transport processes demonstrate success at modelling hydrodynamics and morphology over shorter time scales (Lesser et al., 2004; Roelvink, 2006). Process-based models consider changes in the patterns of circulation inside coastal basins (McLeod et al., 2010; Sampath et al., 2011), portraying different coastline changes and tidal sedimentation scenarios along the same coastal system. Although not specifically developed to deal with climate change impacts, these models can be applied to sector analysis (e.g., shoreline change and storm impact simulations) or to the integrated assessment of coastal vulnerability to SLR. The main examples include Delft3D, developed by Deltares (e.g., Lesser et al., 2004; Tung et al., 2009; Van der Wegen and Roelvink, 2012), MIKE 2D, and the KUTM (the Kyushu University Tidal Model). Comprehensive morphodynamic modelling systems such as ECOMSed, Mike-21, Delft3D ROMS, and TELEMAC–MASCARET (Hervouet and Bates, 2000; http://www.opentelemac.org) generally include different flow modules (from 1D to 3D), a wave propagation model, and a sand transport model including bed load and suspended load (Villaret et al., 2013; see the example in Fig. 7), which allow integrated modelling of complex coastal systems to be performed at different time scales. Van Dongeren and de Vriend (1994), Stive and Wang (2003), and van Goor et al. (2003) have shown that this type of model has the capacity to predict the decadal-scale morphodynamic development of coasts, including the impact of SLR.

With the development of process-based models, the coastal research community experienced a proliferation of numerical methods applications. Although this approach requires a higher level of input data compared with the behaviour models, the output of process-based models provides more detailed information on governing processes (see the examples for highly schematised tidal basins in van der Wegen, 2013). Filtering methods such as tide lengthening or the use of the so-called morphodynamic factor have been extensively applied to reduce computational costs for long-term applications, but such methods also introduce an additional source of uncertainty (van der Wegen and Roelvink, 2008). Many of the models traditionally used to study coastal

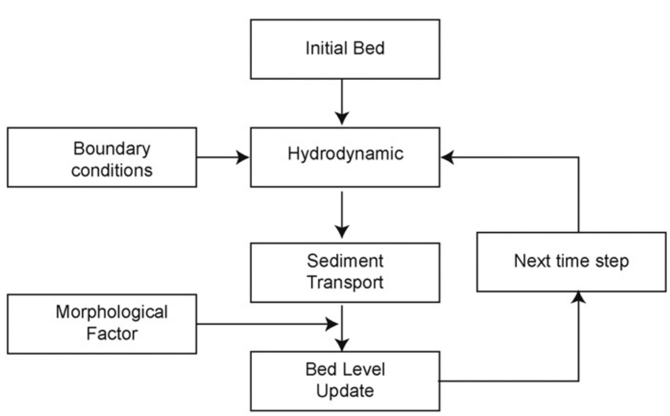

Fig. 7. Schematized diagram of the morphological model in Delft3D (source: Dissanayake et al., 2009).

processes made, by necessity, critical simplifying assumptions that limit their applicability (Ashton et al., 2007). Oversimplification, limited observations, and unknowable future conditions still limit models' ability to make quantitative reliable predictions.

The existing limitations of process-based models concerning the predictability of morphological variables because of the non-linearity of many coastal systems has recently encouraged the development of 'hybrid models' (featuring elements of both top-down and bottom-up models) with simplified dynamics that are designed to predict qualitative behaviour by including only predominant processes (Karunarathna et al., 2008). Recent experimentation includes the model types proposed by Karunarathna et al. (2008) and Townend (2010) for estuaries and tidal inlets. Bayesian networks have also been applied to or can provide probabilistic predictions of shoreline change rates using readily available data on driving forces (rate of sea level rise, wave height, tidal range) and boundary conditions (e.g., geomorphological setting, coastal slope) (see Gutierrez et al., 2011).

A problem highlighted in all research pertaining to morphodynamic modelling is that of the accuracy and verification of results or predictions arising from the numerical calculations. The nature of modelling for predicting future change means that until the predicted change takes place, the model cannot be deemed to be ultimately accurate. The use of models to explore and simulate the operation of contemporary processes in natural science can be an important tool if used wisely and while accounting for limitations and the quality of data required for parameterisation (e.g., Roelvink and Reniers, 2012). However, their use as a long-term, large-scale predictive tool is in its infancy and therefore their value is expected to substantially improve in the future.

4. The economic and social consequences of RSLR for coastal lagoons

A given rate of SLR can have differential impacts on economic and social systems depending on which population groups are affected. Where exposure and vulnerability are high, even non-extreme events can lead to serious consequences (IPCC, 2013; Felsenstein and Lichter, 2014). Thus, the relative burden of coping with the effects of RSLR is more important from a socioeconomic perspective than is the absolute size of the event (Ashton et al., 2007; Felsenstein and Lichter, 2014).

The availability of regional-scale comprehensive vulnerability assessment studies, which are required by local stakeholders for designing adaptation strategies at the local level, is limited (Cooper et al., 2008; Balica et al., 2012). The few studies highlighted in this review include the work of Heberger et al. (2012) for San Francisco Bay, the study of Russell and Griggs (2012) for the California coast (Puget Sound), and the very clarifying perspective of Morris et al. (2012), which predicts that in the absence of anthropogenic barriers, a 1 m rise in sea level would create around 11,000 km^2 of new intertidal area in the conterminous United States alone. Besides, only recently have studies become fully aware of human adaptation measures for facing the undesirable effects arising from RSLR. For instance, Cooper et al. (2008) evaluated coastline displacement and its consequences based on the direct inundation of Delaware Bay (New Jersey), and listed the methodologies that may prove useful to policy-makers despite the large uncertainties inherent in the analysis of the local impacts of sea-level change. Yoo et al. (2011) developed a methodology for assessing vulnerability to both climate change and RSLR in coastal cities. Carrasco et al. (2012) assessed the inundation of backbarriers and proposed several human adaptation measures, focusing mostly on sandy stretches. Raji et al. (2013) used GIS techniques to assess the number of people at risk from flooding, and constructed a socio-economic vulnerability index according to the distribution of land uses across physical vulnerability classes. Other pertinent examples of economic estimates of material losses caused by the consequences of morphodynamic readjustments to RSLR can be found in Ribbons (1996), Anthoff et al. (2010), Merz et al. (2010), and Van Thang et al. (2011), who examined the direct link between poverty and RSLR in the lagoons and coastal areas of

Thua Thien province, Vietnam. Finally, we highlight the study of Cooper and Lemckert (2012), which, although not exclusively dedicated to coastal lagoons, emphasized some of the practical considerations that specifically characterize large coastal resort cities (in the Gold Coast area, Australia). Those authors outlined the potential impacts of 1 m, 2 m, and 5 m of potential SLR, assuming that current occurrences of surges, cyclones, and rainfall would be superimposed on these levels.

The small size and dispersed distribution of coastal lagoons along coastlines can lead to their mismanagement. In addition, administrative frontiers often do not facilitate a coherent management of coastal lagoons (Gaertner-Mazouni and De Wit, 2012). The main economic and social approaches used to face RSLR rely fundamentally on the adaptation and mitigation options. Clearly important for the definition of adaptation measures is to better understand the links between barrier systems, lagoon marshes, and tidal basins (Ashton et al., 2007), and the human frame, and how these features will evolve during RSLR. According to the United Nations International Strategy for Disaster Reduction (UNISDR, 2009), adaptation is '*the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects that moderates harm or exploits beneficial opportunities*'. Some researchers view society as the adaptive unit; that is, adaptation is the ability of a system to return to functionality. Others perceive the unit of adaptation as being the largest and most inclusive group that makes and implements decisions with respect to exploitation in the habitat (Oliver-Smith, 2009). On the other hand, mitigation is the '*lessening or limitation of the adverse impacts of hazards and related disasters, and encompasses engineering techniques and hazard-resistant construction as well as improved environmental policies and public awareness*' (UNISDR, 2009). Mitigation and adaptation are proactive and increase the resilience of a society; that is, increase the capacity to absorb the impacts of hazards that exist in its surroundings without major disruption of basic functions. However, even where RSLR mitigation measures are applied, coastal adaptation still remains essential (Nicholls et al., 2007). The growing populations and economies of the coastal zone reinforce this need. However, the simple implementation of an adaptation measure is not an endpoint; rather, adaptation is an ongoing process requiring the constant prioritization of risks and opportunities, the implementation of risk-reduction measures, and reviews of their effectiveness. Hence, the performance of any adaptation measure (within the scope of an integrated coastal zone management framework) should be carefully monitored during its implementation to improve its maintenance and other future interventions (UNEP, 2010). Only 'no-regret' strategy measures (providing economic and environmental benefits by fostering innovation and economic development) and 'insurance' responses by the insurance industry (dealing with the precautionary principle where RSLR would have large costs) will be appropriate in the next few decades as coastal management actions (Nicholls and Mimura, 1998).

5. A summary of trends

It should be borne in mind that because of regional differences in SLR, the occurrence of and response to the effects of climate change will not be uniform worldwide. The major sources of uncertainty are the projected mean SRL estimates and how and when RSLR will manifest itself at different spatio-temporal scales, and in agreement with the context of local sediment availability. Therefore, the nature of the long-term morphodynamic response of coastal lagoons to RSLR will depend on the type of basin and on the availability of external sediment to meet the increasing sediment demand within the system, as well as on human modifications to the lagoon system. Morphological modelling has been widely used to predict the potential of erosion/accretion at different time scales. In particular, process-based models have been herein considered as important tools for portraying coastline changes and sedimentation scenarios in coastal lagoons in response to different rates of RSLR, but such modelling requires further development and validation.

Unlike infrequent large magnitude storms that can reshape the coast within hours, the impacts attributed solely to SLR are typically slow, repetitive, and cumulative (Fitzgerald et al., 2008). Immediate effects include submergence, increased flooding, and saltwater intrusion into surface water, whereas long-term effects will increase shoreline erosion and induce saltwater intrusion into groundwater as the coast adjusts (Passeri et al., 2015). In addition, coastal wetlands will struggle to keep pace with SLR if sediment supplies are not sufficient (Nicholls and Cazenave, 2010). If a basin has an abundant and continuous influx of external sediment, then it will be able to maintain its morphology and reach a stable state. In the absence of an adequate supply of external sediment, some of the prominent features (salt marshes and spits) are likely to recede or disappear altogether during the adjustment process, and inundation processes will dominate (Reeve and Karunarathna, 2009). The morphological threshold above which features are eroded varies widely, and is largely dependent on changes in the overall erosion and sedimentation context. Wetland loss and RSLR ultimately results in a sink to the regional sediment budget (Fitzgerald et al., 2006). The capture of sand at inlets and within the backbarrier diminishes the sand reservoirs of the barrier islands, leading to breaching and eventually to the formation of retrogradational barriers (Fitzgerald et al., 2006; Walters et al., 2014). From the above review and based on Fig. 5, a conceptual diagram describing the balance between RSLR rates, the sediment supply rate, and induced human stress is proposed in Fig. 8. Under rising sea levels, coastal lagoons embrace two main basin profile responses: inundation and silting-up. A dynamic equilibrium condition is attained when the marsh accretes at a rate that is similar or equal to the rate of RSLR and when there is still sufficient accommodation space for further marsh growth. An overall maintenance of the inlet's geometry and lagoon accommodation space is achieved under such conditions. Basin inundation occurs when the rate of RSLR is too high for the rate of external sediment supply to keep up, favouring shoreward lagoon displacement (Fig. 8). Basin silting-up occurs when there is sufficient sediment supply and a low rate of RSLR; a decrease in the dimensions of tidal inlets is expected, and consequently, a potential decrease in tidal prisms. Human stress increases towards the two extreme scenarios, inundation and silting-up, by a continuous deterioration in economic and social conditions. Basin inundation increases human vulnerability to flooding (increased human stress), and increases the complexity of adaptation measures required to keep pace with high water levels (leading to high protection costs); basin silting-up will affect the lagoon sedimentary patterns, with detrimental consequences for local marine-based industries, such as fisheries, aquaculture, and clam farming (Fig. 8).

The relatively small number of studies integrating potential human vulnerability with SLR in coastal lagoons is perhaps because of our need to continue learning how to interpret SLR itself as well as the associated evolution of coastal areas (Ward et al., 2012). Even if the presented review provides insights to predicting features from projected future conditions, an integrated approach is necessary to fully understand the response of coastal systems to RSLR. Although research is required at all scales, an improved understanding at the physiographic unit scale (e.g., coastal lagoons, deltas, and estuaries) would have particular benefits, and could support decisions made regarding adaptation to RSLR and lead to better coastal management actions. Therefore, a local focus on individual lagoon systems and their potential evolutions over the next decades to a century in response to SLR must be addressed in future research.

6. Conclusions and future challenges

Because we still lack a full understanding around how and when ice sheets will melt, or even about the relevance of the contributions of CO_2 to the atmosphere, uncertainty still surrounds SLR and its potential impacts, and future challenges include the following. First, the lessons learned about the patterns of variation in RSLR need to be more widely

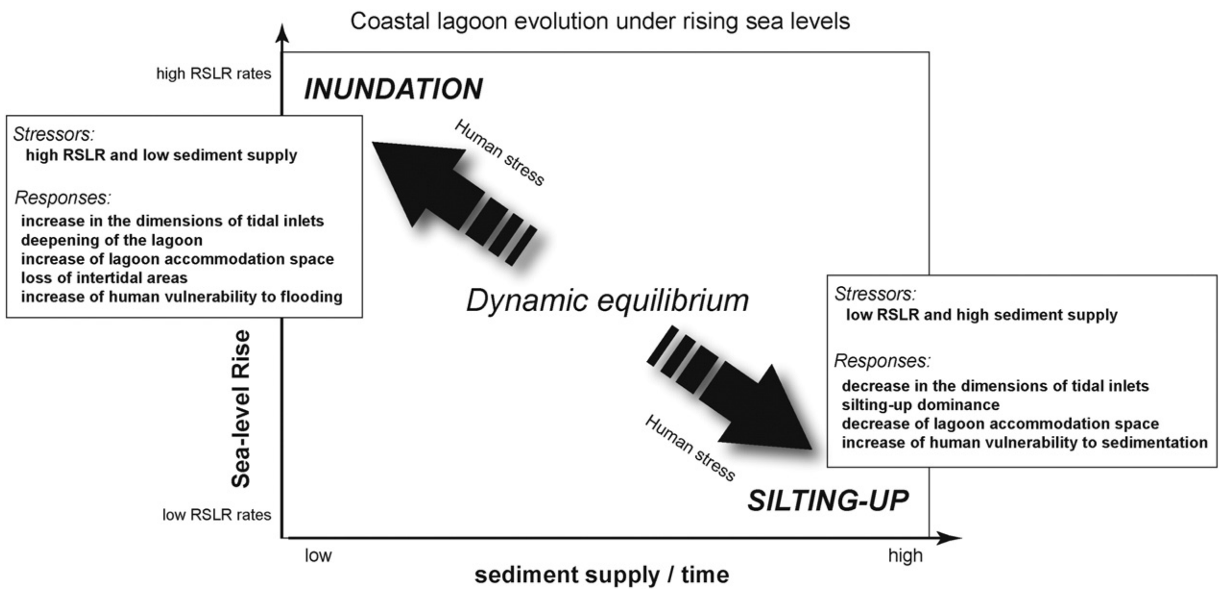

Fig. 8. A representation of lagoon evolution as a balance between RSLR and sediment supply favouring either lagoon inundation or lagoon silting-up. The equilibrium is attained when a marsh accretes at the same rate as RSLR; human stress gradually increases towards the inundation and silting-up extremes.

used to improve the prediction of sea-level change and to further improve management actions to deal with it. Second, conceptual and numerical models of both past and future coastal changes must also contemplate the human role at the coast (Ashton et al., 2007), and the improvement, testing, and validation of such models should be a priority. In general, most studies of nearshore processes have been conducted on long, straight shorelines, and the mechanisms driving shoreline and coastal change along coasts with complicated nearshore and surf zone bathymetry, inlets, headlands, or lagoons are less well understood. Indeed, model uncertainties may be still large, and there is a pressing need for further research to be conducted on these coastal areas. Besides, the morphodynamic variability of coastal features and the relationship of such variability to RSLR is not linear, and the problem of nonlinear, multiple-scale dynamics is still far from being solved (e.g., Dastgheib et al., 2008). Third, the analysis of RSLR scenarios and predicted impacts, as well as the estimation of possible damage and losses, is still not fully integrative up to some scales (Yohe and Tol, 2002). For example, the costs of land loss due to increased coastal inundation, the cost of forced migration due to permanent inundation, and the impacts of RSLR in combination with other drivers acting on ecosystems have not been assessed at local scales (e.g., Gornitz et al., 2002). The rates of change of coastal lagoon shorelines are also of interest where wetland regeneration is concerned, for the conservation of threatened species (Reed, 1995), for the flood-buffering properties of vegetation (Townend and Pethick, 2002), and in the burgeoning field of carbon sequestration (e.g., Morris et al., 2012). Accordingly, the non-market value of ecosystem services must be used to promote the conservation, restoration, and creation of wetlands in coastal lagoons, and to protect adjacent uplands from wetland transgression (Kirwan and Megonigal, 2013).

Several questions still need to be answered, the most important of which are as follows: (1) To what extent are the observed changes locally important from the natural and social–economic–cultural points of view? And (2) To what extent will global mitigation measures prove adequate for local cases? These questions are often associated with a difficulty in conceptualizing and quantifying the main expected responses (from the natural and social–economic–cultural points of view). The 'commitment to sea-level rise' (Nicholls and Tol, 2006; Nicholls et al., 2006) should be 'for life'. Moreover, when efforts to reduce climate-related risks to coastal systems are reactive and standalone, they are less effective than when they are part of an integrated coastal zone management (Nicholls et al., 2007). Integrated coastal zone management is recognized as the most appropriate framework to deal with climate change, SLR, and other current and long-term coastal challenges (Nicholls and Klein, 2005). Proactive adaptation to climate change aims to reduce a system's vulnerability by minimizing risk and/or enhancing the system's resilience. With adaptation planning proliferating as a strategy for managing the risks of climate change to coastal systems, attention is beginning to shift towards evaluating how effective such planning has been. The precise boundary between what is appropriate at the national and regional levels may be fuzzy, and in many cases regional/local-scale efforts, compared with the adoption of national-scale policies, will become more efficient in terms of achieving adaptation (Nicholls and Mimura, 1998). To effectively cope with RSLR and its impacts, current policies and economic considerations should be examined, and possible options for changing planning and management activities warranted, so that both society and the natural environment can more effectively adapt to potential acceleration in SLR.

Scientific topics needing to be explored and detailed in the future include:

- Downscaling SRL effects from the global level to regional and local levels in order to typify and identify the evolution for individual coastal lagoons;
- Improving the reliability of model scenarios/predictions, accounting for the effect of RSLR jointly with extreme events on the evolution of coastal areas;
- Defining ecological losses/shifts and how they interact with morphological shifts, including feedback mechanisms that are not yet completely understood or modelled (e.g., the synergetic approach as recently proposed by Passeri et al., 2015);
- Defining how to implement increases or decreases in sediment deposition rate inside lagoons in conceptual and numerical models in a quantified way and including the morphodynamic responses of the systems; and
- Evaluating the impacts of RSLR on coastal communities and the effectiveness and efficiency of adaptation interventions.

An understanding of the interaction between the natural and the human subsystems is critical to gaining a comprehensive understanding of human vulnerability in coastal lagoons and should include the role of institutional adaptation and public participation. Determining what to protect, how to pay for it, and how those choices are made also raises concerns with respect to equity and to social, cultural, and environmental justice that must be fully addressed in any proposed coastal management solution.

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